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Advancing Automation and Robotics Technology for the Space Station Freedom and for the U.S. Economy

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The February 1990 issue of the AIAA monthly publication "Aerospace America" featured NASA's Flight Telerobotic Servicer element of Space Station Freedom with six articles and the front cover photograph. The cover shows one concept for an end effector under evaluation in the robotics development facility of the NASA Goddard Space Flight Center. In the photograph the end effector is reaching for a Space Station Freedom structural attachment point to tighten an equipment support leg.

baseline SSF. This activity is often referred to as the "scrub" or "program rephasing." One change (resulting in part from the review) which may have significant impact with respect to robotics is the program's decision to terminate the development of a new extravehicular activity (EVA) suit. This decision has prompted increased use of teleoperation and robotics for the SSF. While the full impact of the decision has not yet been determined, the current overall SSFP environment suggests that the FTS has received increased attention for use on SSF operations. Specifically, recognition of FTS usefulness for aiding in the assembly of Space Station Freedom has occurred, and activities are under way to plan for its use.

The program rephasing also has affected advanced automation efforts. In ATAC Progress Report 9, two advanced applications of automation were listed as part of the SSFP baseline. One of these was an on-board capability for system failure detection, isolation, and reconfiguration, and the other was for platform anomaly diagnosis. The first of these was terminated in the program rephasing; the second automation application has been effectively transferred out of SSFP by the assignment of platform responsibility to the Earth Observing System (Code E). **These changes leave SSF with no baseline applications of expert systems.**

In addition to design related changes, offices and managers for the integration function for the SSFP have been established at Johnson Space Center and at Marshall Space Flight Center. These functions were formerly located in the Level II office in Reston, Virginia.

Budget considerations also have been an important part of the climate for SSF development. The OSS Advanced Development Program was subject to significant budget fluctuations during the year, but despite the adverse impact of these fluctuations, the program was still able to fund a number of A & R development tasks. In addition, the A & R program of the Office of Aeronautics, Exploration and Technology (OAET) (formerly the Office of Aeronautics and Space Technology (OAST)) and the OSS Advanced Development program have cooperated in cofunding several tasks. The first space demonstration test flight (DTF-1) of the FTS was rescoped as a result of budget problems but is on (a very tight) schedule. The rest of the FTS program has not been adversely impacted by budget considerations and remains on track.

Another significant part of the climate for SSF is the need for accommodating growth and evolution. A near-term aspect is the requirement to provide transition for A & R technologies from the permanently manned capability (PMC) to the assembly complete (AC) version of the baseline Space Station Freedom. The PMC is the point at which the SSF assembly sequence provides a habitable pressurized module with necessary life support, power, and other resources so that an astronaut crew can operate without the SSF being attached to the Space Shuttle. The PMC should occur about halfway through the assembly sequence. The AC is the point at which the baseline SSF is completely assembled. The estimated number of assembly flights varies, but should require approximately 22 flights over a 4- or 5-year period. Ensuring that A & R technologies can be implemented by AC given the PMC design is a substantial challenge for the SSFP.

The interest in the Space Exploration Initiative also motivates the need for growth and change of the SSF. The implementation of the Lunar and Mars missions will very likely require significant enhancements of the A & R capabilities of the SSF. Thus the climate enhances the already significant need for A & R on the SSF.

sequences, and resources associated with assembly are being allocated between FTS and astronaut EVA. This planning reflects back into the design of the FTS and robot-friendly structures. There is thus an emerging commitment to use robots and a recognition of the need to develop greater robot capability. Plans are being developed for some limited areas of A & R. **Nevertheless, ATAC continues to believe that the overall, detailed A & R plan it has recommended should be completed, approved, and published to ensure that the appropriate priorities and commitments are recognized and implemented throughout the entire program.**

The ATAC Progress Report 9 recommendation II was as follows:

> **"(II.) Establish a hierarchy of full-time dedicated A & R focal points in Levels I, II, III and the Work Package contractors. Develop specific responsibility statements for each focal point, including hierarchal interrelationships, program overview/visibility responsibilities, program management access methodologies, and other factors needed to ensure that the focal points have program visibility and management access to ensure that A & R is properly considered in the SSFP. Delays and regressions experienced in developing these A & R focal points and hierarchy reflect a perception of a low priority for A & R development by management."**

A similar recommendation appeared in ATAC Progress Report 8. Despite repeated recommendations of this nature, the situation described in Progress Report 9 still has not changed appreciably. Level II has recognized the importance of coordinating and managing the implementation of A & R, and has named people within its organization to serve as focal points for robotics, for advanced flight systems automation, and for advanced ground systems automation. The ATAC is encouraged by these appointments, but is concerned by the frequent reassignments and lack of specific responsibilities in the Level II focal points. This situation interrupts continuity of the focal points in contributing to, assessing, and reporting on A & R plans, analyses, designs, resources, and accomplishments. Despite this situation, the personal initiatives of the individuals involved have led to progress in the robotics area. Specific examples of this are the planning activities for the utilization of the FTS and the development of the Robotic Systems Integration Standards (RSIS) document. Nevertheless, because the focal points generally are not dedicated to A & R full time and because their roles with respect to A & R are not yet clearly defined, ATAC is not convinced that the desired improvement in implementation of A & R in SSFP will occur as a result of these appointments.

Level I has an A & R focal point who continues his energetic support of ATAC and A & R activities and has focused the Level I Advanced Development Program on technology activities intended to advance and validate applications of A & R. Moreover, the Work Package Centers have generally appointed focal points for A & R.

In summary, individuals are identified in most organizations to be the A & R focal points. However, these individuals generally have responsibilities that are not clearly defined as well as other demands on their time that severely limit their attention on A & R activities. This situation gives the perception that there is very little commitment at all levels of management to the implementation of A & R.

In order to ensure that the SSF development takes full advantage of the potential benefits of A & R, ATAC believes that the organization must include a hierarchy of focal points with clearly defined roles and responsibilities that give them visibility throughout the program and permit the necessary standardization and compatibility of hardware and software across complex distributed systems. The duties for these personnel would be distinguished from those in a line organization responsible for producing the systems. The focal point must advocate employment of technology derived from the Advanced Development Program, wherever advisable, and must propose prototype verification tasks where necessary to build confidence in a new technology. Dedicated A & R focal point positions with clearly defined responsibilities and roles are important throughout the space station organization. The ATAC notes that positions with the necessary characteristics have not yet been established.

The ATAC Progress Report 9 recommendation III was as follows:

> **"(III.) Develop objective criteria for evaluating all SSFP technologies including A & R to ensure that A & R technologies are evaluated on an equal basis. In addition to evaluating**

of prior ATAC comments, Level I has strengthened its program by including it in the program operating plan (POP) call and has requested that other NASA codes assist in evaluating its programs. The ATAC feels that it is also very desirable that Level III should also participate in the evaluation of proposed high-leverage prototyping projects. The efforts of Level I to support appropriate high-leverage prototyping activities in the face of zero Level II funding for activities of this type highlight an apparent disconnect in management philosophies of the various levels with respect to A & R. The ATAC strongly believes that the overall budget for advanced development and high-leverage prototyping efforts are inadequate and must be increased and kept stabilized. Moreover, significant Level II participation must be present if automation technologies are to have the most desirable impact on SSF life cycle costs in the future. **The Level I Advanced Development Program is currently a major automation and robotics driver for the Space Station Freedom Program; therefore, funding stability for the program must be ensured and funding increases should be emphasized.**

The ATAC Progress Report 9 recommendation V was as follows:

> **"(V.) A unified and formal organizational structure needs to be developed to define all FTS tasks, especially those involving assembly sequences. The FTS must be considered as a resource during development of EVA activities, especially as a contingency for maintenance activities during assembly sequences. Previous working groups considering FTS and EVA activities have had informal coordination; however, a lack of formal recognition and interaction has delayed identification and acceptance of FTS tasks and capabilities."**

Very significant progress has been made with regard to recommendation V. Information on suitable FTS task assignments has been developed by the FTS Mission Utilization Team. This team, with the help of information supplied by the Work Packages, has identified activities for the first three manned-base flights, especially the third flight, where the EVA demands are the greatest.

In addition, there are now two groups formally chartered to analyze FTS applications. Both reside in Work Package 2 (the FTS user), and they have the highly desirable attribute of sharing some common members. The External Maintenance Task Team is assessing the requirements of intravehicular activity (IVA) operator time and the cost of robot-friendly design for allocating external maintenance to the FTS. (The report is scheduled for July 1, 1990.) The Assembly Planning Review Team is examining the assembly sequence and aiming at a workable distribution of tasks among EVA, IVA, and robotics. (Their report was due March 1, 1990.)

Many assembly tasks are considered to be suitable for the FTS. These include inspection, operation of latches and attachments, and deployment of elements of the Mobile Transporter, Astronaut Positioning System and Assembly Work Platform. These tasks are less repetitive than some other assembly operations and require a level of dexterity and flexibility that are considered well within the design goals of the FTS. The Assembly Planning Review Team has initially determined that truss beam assembly is better suited for EVA, in part because the FTS requires a supporting infrastructure which is currently not well defined. The FTS mobility, hardware compatibility, and ground support are issues of this infrastructure that still need refinement and agreement among SSFP management and the Work Packages. The ATAC is concerned about the sparse attention being paid to supporting infrastructure for the FTS and feels that more attention must be paid to this area to ensure that the FTS can support a wider variety of assembly tasks.

The ATAC is hopeful that the findings of these two teams, if enacted through the change request process, will resolve a key, long-standing, and still present weakness of the FTS: lack of assigned tasks. In this regard the FTS project should be commended for having readied the Task Analysis Methodology which is helping both groups. Also, Work Package 2 is to be commended for seeking input for assembly capabilities of the FTS and for considering them in the assembly planning process.

The activities described above show that levels of management in the Space Station Freedom Program now appear to recognize the necessity of telerobotic capabilities and the need to define tasks for which the FTS can be used efficiently. The ATAC judges these developments to be very important and to be appropriate steps in the process of defining the role and utilization of the FTS resource. The ATAC hopes that after almost 3 years since inception of the FTS project, such definition by the SSFP may be at hand.

the equipment, procedures, tools, and training. It will be just as necessary to perform the analogous evaluations for telerobots which will perform functions in space. This study will attempt to define what types of facilities will be necessary to ensure that adequate attention is given to the ground infrastructure.

The Advanced Development Program also has been supporting the development of advanced automation prototypes which are being or will be implemented in the SSF test beds. These on-board applications include power management, distribution, and control; environmental control and life support system; and a thermal control system. They focus heavily on fault detection, isolation, and reconfiguration capabilities and are a mix of conventional and knowledge-based system (KBS) techniques. There are also projects for ground-based applications which include the mission control centers, software support environment (SSE), and the Technical and Management Information Systems. These applications are also a mix of conventional and KBS techniques, and each provides a comprehensive user interface to support advisory mode interactions.

In addition, the Advanced Development Program supports the development and evaluation of software tools for the SSE and advanced processor or multiprocessor and networks for advanced SSF data management system capabilities.

Finally, the Advanced Development Program supports development of robotic systems technology. The emphasis for this area is on the development of sensor and control algorithms and architectures to increase the efficiency and productivity of the FTS and to develop the necessary technology component to enable supervised autonomous operations and the eventual ground-remote teleoperation of the FTS. (Appendix A, written by Level I, describes the Advanced Development Program in more detail.)

Overall, the Advanced Development Program has done yeoman work in this regard, despite the funding troubles mentioned above. The program has been helped by OAET's cofunding of some tasks, a development which points to improved coordination between the two programs. The ATAC feels that the program is to be commended; however, the program can be improved by more stable funding and by more formal involvement of the Work Package personnel and Codes M, R, and E in the task selection process. **Repeating an earlier recommendation, the Level I Advanced Development Program is the major driver for evolution of automation and robotics for the Space Station Freedom Program; therefore, funding stability for the program must be ensure and funding increases should be emphasized.**

OAET A & R Program

Since the last ATAC report, OAET programs in artificial intelligence and telerobotics have been restructured and more closely coordinated with the Space Station Advanced Development Program. After absorbing budget cuts on the order of 15 percent for FY 90, the restructuring focused programs on applications of artificial intelligence technology and of telerobotics technology. The applications for artificial intelligence include intelligent assistance for mission operations; scientific and engineering data analysis techniques; autonomous on-board fault detection, isolation, and reconfiguration (FDIR) and control; and capture, integration, and preservation of life-cycle knowledge. The telerobotic applications include assembly and manipulation of large structures and vehicles on-orbit; remote manipulations on-orbit controlled by operators on Earth; and pre- and post-launch processing cost reduction. During FY 89 OAET also added the Planetary Rover Program for manned and highly autonomous rovers for the Moon and Mars. The initial focus of this program is an automated, unmanned, planetary rover for exploration and scientific investigation.

The OAET A & R program has been having an impact on NASA's way of doing business. This program initiated the INCO expert system, which became the Real-Time Data System (RTDS), for shuttle mission control. After this initial success, the user programs (NSTS and SSF) added funding to accelerate and complete the development. (See Appendix A for more information.) Also, at JPL, the SHARP system, which is analogous to INCO for unmanned missions, was demonstrated during the Voyager flyby of Neptune. It is now being considered for use by the Deep Space Network and the Galileo and Magellan projects at JPL. **The ATAC assessment is that both the OAET closer coordination with the SSFP and increased focus on applications, while maintaining a balance of more basic research, are worthwhile and laudable steps at this time.**

Flight Telerobotic Servicer

The FTS was extensively reviewed by ATAC in Progress Report 9. Based on additional information considered for this report, ATAC believes that innovative computer systems, such as multiprocessors, or distributed processor applications. A DMS which is flexible and accommodating of a wide variety of computer architectures will best meet the needs of the space station user community and system automation technology. **User automation and robotics requirements for the Data Management System and Operations Management System must be identified as soon as possible to ensure that the baseline system designs will support SSF transition and evolution, especially A & R implementations.**

The OMS Fault Management (FDIR) expert system baseline effort was presented as an automation effort that the DMS must support. Unfortunately, it appears to ATAC that the DMS memory may be inadequate for supporting this application and probably other A & R applications. It is clear that FDIR requirements are disconnected from the DMS design approach. As presented, it also appears to ATAC that there is a disconnect between overall FDIR strategy and subsystem FDIR strategy. Specifically, the role of OMS FDIR compared to each subsystem FDIR is not clear. The ATAC is of the opinion that an FDIR approach should address both the overall OMS FDIR strategy, as well as the subsystem FDIR strategy.

In addition, there appeared to be no provision for temporal fault propagation in the presented baseline OMS FDIR approach. However, the non-baseline OMS test bed demonstration did include temporal fault propagation effects. The ATAC is concerned that the static approach is not sufficient for the baseline OMS.

The baseline SSFP should have an OMS test bed. The opportunity to test developments in context would help alleviate these problems. Since the OMS is a gateway for advanced technology, it needs to be well defined and recognized as an integral part of the SSFP. The current OMS test bed at NASA/JSC is not funded by the baseline program or supported sufficiently to address the need for testing. **The SSF baseline program should have an Operations Management System test bed to ensure that the software and other items are properly integrated and to provide a means for automation technology testing and comparative analyses with non-automated technologies.**

APPENDIX A

Office of Space Station Automation & Robotics (A & R) Progress

The Space Station Freedom Program (SSFP) policy for A & R reflects a commitment to apply A & R technologies in the design, development, and operation of the baseline space station. A & R applications will be utilized when found to be appropriate within the context of the overall system design, to have a favorable cost-to-benefit ratio, and where the enabling technology is sufficiently mature. The program recognizes that A & R technologies are experiencing rapid change, exhibit varying levels of technology readiness, and have unique requirements for successful integration with conventional design approaches and system engineering methodologies. Consequently, an important component of the SSFP A & R policy is the provision of design accommodations and mature technology which will permit the program to fully capitalize on the anticipated A & R advances which will occur during the development and evolution of Space Station Freedom. Last, the program intends to take full advantage of the significant momentum in A & R research and technology development within the governmental, industrial, and academic sectors during all phases of the program.

Progress has been made by the SSFP in each of the above areas and will be described in the following sections.

A & R Planning and Coordination Activities at Level I

Survey of Astronauts Concerning A & R Applications

To understand better the ability of A & R technologies to beneficially impact productivity on the station, Level I sponsored a study that analyzed lessons learned from previous space missions, assessed crew time requirements for the station, and also conducted a large number of interviews with current and former astronauts to document their experiences and preferences for A & R applications. The final report, entitled "Space Station Freedom Automation and Robotics: An Assessment of the Potential for Increased Productivity," documents the study results.

The study data and analysis supports the conclusion that there are a number of A & R applications which are presently supported by available technology and which have a high potential to significantly impact productivity, and that have been strongly supported by the astronaut community during the interviews and questionnaires. The A & R application categories, as well as guidelines for the selection of applications and their subsequent development, are provided in this report.

Many of the applications reviewed are presently under development and evaluation within the Advanced Development Program. The results of this study will be used to influence the content of the on-going tasks and to plan future A & R application development.

Advanced Automation Evolution Study

To aid in program planning for the development and evolution of advanced automation, the Advanced Development Program funded a review of program capabilities. The final report, entitled "Space Station Freedom Program Capabilities for the Development and Application of Advanced Automation," summarizes the development and evaluation of applications for flight and ground systems within the design and research organizations, the engineering test beds, and also covers the existing tools and applications in operational use within NASA. In conjunction with this review, a three-volume report was prepared which addresses issues associated with the development, use, and evolution of advanced automation technology within the program.

The first volume, "Evolution Paths," identifies issues which impede or accelerate the development and transition of applications which use advanced automation and provides recommendations for establishing environments within the program which enhance the implementation of automation technologies. The second volume, "Evolution within the Test Beds," outlines a methodology and recommended plan for the insertion of advanced automation technology based on experiences to date with the implementation and integration of advanced automation software on program engineering test bed facilities. The third volume, "Evolution with Environments," presents concepts to permit the transitioning of advanced automation software technology and applications between the engineering test beds and the software production facilities. Recommendations to increase the support of advanced automation by the Software Support Environment (SSE) are provided.

Major accomplishments during this reporting period include:

Mature PMAD FDIR application and user interface software on the Marshall Space Flight Center (MSFC) PMAD test bed is being re-hosted to a computer architecture compatible with the space station Data Management System (DMS) hardware and software to closely evaluate DMS implementation and performance issues. Integration of conventional software and hardware FDIR with advanced KBS techniques will continue and will be evaluated on the test bed. Analysis of KBS interface and communications requirements for a distributed, cooperating KBS demonstration has been completed, and a link with the Lewis Research Center (LeRC) PMAD test bed has been established.

Failure diagnosis and isolation and associated fault explanation capabilities have been implemented in the KBS for PMAD switchgear on the Lewis Research Center (LeRC) PMAD test bed, and an electrical load scheduler has been integrated with the diagnosis and isolation KBS to implement intelligent re-scheduling of power loads in contingency situations. Initial testing of these applications using brassboard hardware and high-fidelity simulations will be conducted during the remainder of FY 90. Preparations for a joint demonstration of distributed, cooperating KBS applications between the LeRC and MSFC PMAD test beds have been completed, and a joint test plan is in preparation. The joint LeRC-MSFC demonstration will examine requirements for distributed cooperating KBS applications and evaluate global FDIR requirements for a major distributed system on the space station.

An Environmental Control Life-Support Systems (ECLSS) design accommodation analysis has been completed which examined automation requirements and implementation issues for KBS FDIR of major ECLSS sub-systems. A potable water quality monitor prototype was developed and will be demonstrated using inputs from a high-fidelity simulation. The KBS development tools which use the Ada language will be evaluated as part of the ECLSS automation task. Additional prototypes will be developed in FY 90 and FY 91 and demonstrated on the ECLSS test bed at MSFC.

As an outgrowth of the successful demonstration of the OAST-funded Thermal Control Expert System (TEXSYS) prototype developed by Ames Research Center (ARC) and Johnson Space Center (JSC), a task was initiated in FY 90 to capitalize on the lessons learned and transition the experience gained to the space station Thermal Control System (TCS). A KBS FDIR prototype is being developed using hardware and software representative of the baseline space station and will be demonstrated using operationally accurate simulations and test bed hardware. This activity is jointly managed by a senior Thermal Engineer and the Work Package 2 Functional Manager for Advanced Automation, participation by the prime contractor and principal subcontractor for the TCS is expected.

A prototype KBS experiment protocol manager has been developed at Ames Research Center (ARC) and the Massachusetts Institute of Technology (MIT) which restructures a life sciences experiment upon request when faulty instruments, time shortages, or interesting data are encountered. The prototype has been developed for a Spacelab-based vestibular physiology experiment (manifested on SLS-1 and SLS-2). The initial prototype has demonstrated that KBS techniques can significantly improve the astronaut's ability to perform in-flight science and provides protocol flexibility, detection of interesting phenomena, improved user interface for experiment control, real-time data acquisition, monitoring, and on-board troubleshooting of experiment equipment. The system, known as PI-in-a-box, is being ground-tested in the Spacelab Baseline Data Collection Facility in support of the SLS-1 mission and will be used in-flight on SLS-2. The experience with pre-flight, flight, and post-mission data on the SLS-1 and SLS-2 Spacelab missions will be used to influence design requirements for Space Station Freedom laboratory experiment interfaces to ensure that analogous capabilities are provided. Crew members and the experiment's Principal Investigator are actively involved in the development and evaluation.

In Ground Operations and Information Systems, advanced automation applications and the computer and network architectures required to enable them are being addressed. Applications are been initiated with MSFC Work Package 1 personnel (NASA and contractor) to select a baseline engineering design application to evaluate the initial version of the tool. Level II has provided funding to support the transition and evaluation of DART.

Progress also has continued in tasks which are developing software tools to support the development of advanced automation applications. A prototype programming environment for generating Intelligent Computer-Aided Training (ICAT) systems is well under way at JSC. The ICAT application development environment permits an instructor and training development personnel to build software which uses multiple KBSs to customize training scenarios and track student progress. Initial MCC training applications have been developed using ICAT tools and evaluated against ground operations training requirements. When completed, the ICAT environment will greatly reduce the time and expense of developing computer-based training systems and significantly increase student performance while requiring shorter training times. Components of the ICAT technology have been "spun off" to the education community. Private sector funding is developing a high school physics tutor using ICAT technology. It is expected that other applications for Chemistry and Mathematics will follow.

The development and evaluation of Ada-based KBS programming tools and run-time environments will yield two prototypes for evaluation in early FY 90, one is derived from Inference Corporation's ARTTM product and the other is based on the NASA/JSC developed CLIPS tool. Each will be evaluated using existing KBS applications, and the detailed design requirements for transition of tools to support KBS application development within the Software Support Environment (SSE) will be developed. These programming tools will permit the development of advanced automation applications in the Ada programming language which has been baselined for flight system software. A second prototype of an Automated Software Development Workstation (ASDW) has been delivered to JSC and is being evaluated by the Mission Operations Directorate for use in MCC software maintenance. The ASDW provides a KBS interface which assists the programmer in rapidly developing large programs through the reuse of existing Ada software modules. The ASDW is under evaluation for incorporation in the space station SSE to support station software development and maintenance.

In Robotic Systems Technology, an emphasis has been placed on the development of sensor and control algorithms and architectures to increase the efficiency and productivity of the Flight Telerobotic Servicer (FTS) and to develop the necessary technology components to enable supervised autonomous operations and the eventual ground-remote teleoperation of the FTS. As fully automated control of the FTS is not a viable near-term option for augmenting EVA, it appears that ground teleoperation, for simple tasks such as inspection, provides a way to reduce the EVA requirement and avoid replacing it with an expanded IVA requirement. Refinements and extensions of the NASA Standard Reference Model (NASREM) control architecture to better integrate technological advances in sensing, perception, and control will be one of the products of the tasks under way. Additionally, the design of "robot-friendly" interfaces and assembly/maintenance procedures is being addressed for post-baseline robotic assembly, maintenance, and servicing operations.

Major accomplishments during this reporting period include:

An EVA-robot task analysis model and computer-based tool has been developed at the Jet Propulsion Laboratory (JPL) to assist in EVA-robot task assignment tradeoffs and component technology assessments. A semiautomated data base management system has been added to the model, and over 200 copies are to be transferred to Level II, the FTS Project Office, the Level III Work Packages, the Mission Operations Directorate, and the Astronaut Office at JSC.

A tradeoff study for an Intravehicular Activity (IVA) laboratory module robot been completed at MSFC. Primary housekeeping and servicing tasks have been identified, and the design of a mockup and robot application task using Spacelab racks and materials processing experiments will proceed as funding becomes available in FY 91.

The Langley Research Center (LaRC) Automated Construction test bed task is progressing well. The tailored end effector for handling/installing truss struts has been completed and integrated with the robot. The overall system includes a jigging fixture for the truss structure, the robot/end effector (attached to a moveable platform), and the truss member storage cannister. At present, the system has been able to consistently assemble the inner ring (24 truss members)

A & R Evaluation Criteria

A briefing was presented on the Level II Life-Cycle Cost Model. Plans were presented for including Robotics as one of the elements of the model and conducting evaluations of the cost effectiveness of Robotics applied to various external assembly and maintenance tasks on Space Station Freedom. The model would keep track of all resources consumed by the Robotic Systems as well as those provided by the Robotic Systems. The one-for-one relationship of Telerobotic Task Times to Telerobotic IVA Operator Times was highlighted as well as the reduced dexterous efficiency of performing external tasks telerobotically as opposed to EVA. A demonstration of the operating computer Life Cycle Cost Model was given to interested members of ATAC.

High-Leverage Prototyping

Past reports to ATAC identified Level II plans to fund prototyping of high-leverage applications of A & R Technology. High-leverage applications of A & R technology are defined as those which would have a sufficiently high probability of success and a sufficiently short prototype demonstration schedule to be considered for insertion in the baseline Space Station Freedom Program. Proposals were requested from NASA Centers and space station Program Contractors; however, none was funded. Many of the concepts identified in proposals for High-Leverage Prototyping are now included in the Level I Advanced Development Program. Level II intends to address transition of the Level I program products to the Space Station Freedom Program in those areas where application of the technology could significantly alleviate EVA, IVA, and Robotic resource allocations.

Assembly Sequence

The current baselined Space Station Freedom Program Assembly Sequence was presented. The baselined assembly sequence manifests the Flight Telerobotic Servicer at First Element Launch. A copy of the Stage Summary Databook, dated December 21, 1989, was provided to the ATAC chairman. Level II plans to develop an Assembly Sequence Expert System were presented. This development will leverage an Ames Research Center Small Business Innovative Research Contract with ISX Corporation for Expert Decision Aids for the space station program. The initial system will incorporate summary level assembly sequence rules and constraints compatible with the assembly sequence guidelines managed by Level II. Once the expert system is complete for Level II application, consideration will be given to incorporate more entailed assembly planning rules and constraints such as those which are a part of the Assembly Planning Review (APR) activity at JSC.

Definition of Tasks for Flight Telerobotic Servicer

Assembly tasks are being worked by the FTS Mission Utilization Team (MUT) in conjunction with Level II chartered Assembly Planning Review (APR) at Johnson Space Center. Potential tasks have been identified and are being analyzed by the MUT. Necessary modifications to assembly plans and hardware will be identified and assessed. Final sanctioning of FTS Assembly Tasks will proceed from the Assembly Operations Assessment (AOA) at JSC. An initial allocation of assembly tasks for the FTS is anticipated in April 1990. External maintenance tasks for dexterous manipulators (FTS and the Canadian Special Purpose Dexterous Manipulator) are being assessed by the External Maintenance Task Team (EMTT) at JSC. This assessment will include recommendations as to which external maintenance tasks are compatible with telerobotic systems, the EVA, IVA and Telerobotic times required to accomplish the required maintenance, and recommendations for "robot friendly" tool and Orbit Replaceable Unit designs which could be standardized across the Work Packages and international partners. These recommendations will be assessed by the Robotics Working Group and the EVA Systems Working Group. Appropriate Interface Definition Documents, Interface Control Documents, and Common Item Lists will then be generated and implemented across the program. The program documents which will identify specific assembly, maintenance, and servicing tasks to be performed by FTS are the Assembly and Maintenance Implementation Definition Document (AMIDD), prepared for Level II by JSC, and the Servicing System Implementation Definition Document (SSIDD), prepared for Level II by Goddard Space Flight Center.

Impacts of Program Rephasing on A & R

The recent program rephasing known as "Scrub 89" had a significant impact on the space station capability to support advanced automation. This impact is centered around the effects of the program rephasing on the Data Management System (DMS). The number of Standard Data Processors has been decreased from 21 to 19, and functions once performed by Embedded Data Processors (EDP's) have been transferred to the core network.

A & R Activities Within Work Package 2

The following paragraphs describe advanced automation projects being developed within Work Package 2 at JSC, largely funded by supporting development. The applications described are not presently within the baseline program, but have the potential to influence the baseline design to better support advanced automation, and, if successful and with appropriate funding, to be incorporated in the baseline program at a later date.

Operations Management System (OMS) Test Bed.—

Space Station Freedom operations management and command and control concepts will be implemented by the OMS. The OMS comprises both ground (Operations Management Ground Application—OMGA) and flight (Operations Management Application—OMA) components. The JSC OMA prototype, when combined with the Data Management System (DMS) and other distributed system test beds, provides a representative OMS Test Bed capability to evaluate global control and automation techniques for station operations management.

An application prototype funded by supporting development that provides monitoring and control of the Operations Management Application(OMA), as well as on-board systems and elements, has been developed. It is written in Ada, X-windows, and OASIS, a prototype User Interface Language. It resides on the OMS/DMS test bed, and its algorithms make use of control features and other standard services of OASIS and represent an efficient conservative approach to control.

An advanced prototype OMGA Execution Monitor is being developed which can support elements of the Space Station Control Center (SSCC) integrated status assessment capability. This program has some elements of expert system capability embedded in it and runs on the OMS test bed. In conjunction with this task an evaluation of Digraph Matrix Analysis techniques to provide more comprehensive FDIR support for SSCC ground controllers is being performed. This would specifically provide a replacement for the existing software (s/w) used in with the Space Shuttle. The existing software is too slow for real-time use and requires considerable maintenance.

Advanced Automation Methodology Project.—The Advanced Automation Methodology Project (AAMP) was created to investigate the adequacy of s/w engineering methods currently planned for SSFP conventional s/w development for the development of advanced automation s/w. The project uses a rigorous conventional s/w engineering methodology based upon an interpretation of the Software Management and Assurance Program documentation standards issued by NASA-HQ and adopted by the SSFP. The project investigates this methodology's effectiveness by using it to manage the development of two advanced automation projects described below: the Advanced Automation Network Monitoring System (AANMS) (produced at JSC) and the Recovery Procedures Generation Application (produced by the WP-2 prime contractor).

Advanced Automation Network Monitoring System.—The Advanced Automation Network Monitoring System (AANMS) will provide continuous monitoring in real time, of a test bed, created in the Intelligent Systems Laboratory, of an FDDI (Fiber Distributed Data Interface) local area network. It will be capable of intelligent identification of network faults and advising the operator of correct operations for recovery. Future versions of this project will be extended to develop intelligent monitoring of network activities to analyze trends in network behavior for predictive diagnosis and detect security violations (such as illegal network usage or information access violations) and malicious autonomous network invasion (such as computer viruses, worms and Trojan horses).

Recovery Procedures Generation Application (RPGA).—The Recovery Procedures Generation Application project will develop a system which intelligently selects the appropriate recovery procedure for a C & T system failure based on the particular failure and the context within which the failure occurred. It will be integrated with other JSC-developed AA system s/w for C & T system FDIR and demonstrated within the C & T test bed at JSC. The work is being performed by the WP-2 prime contractor and coordinated with the C & T system design group and the C & T system subcontractor.

Space Station Health Exercise Monitoring and Control System.—This project is developing a knowledge-based monitoring and control system to support the design of the Health Exercise Monitoring and Control System of Space Station Freedom. It will analyze noninvasive measurements of deconditioning and advise exercise countermeasures on-orbit. The system will be used to generate specifications for integrating a medically oriented symbolic processing system into the Space Station Freedom Data Management System. The system hardware currently consists of a 386 microcomputer and a LISP machine (for control of the user interface and to provide voice synthesis, displays, storage of data, planning, executive control, and management

APPENDIX B

Flight Telerobotic Servicer Progress

Summary

The Flight Telerobotic Servicer (FTS) element of the Space Station Freedom (SSF) Program has completed transition from the definition phase into the development phase during the past six months. Significant progress has been made in the interface definition with SSF and a process has been established to baseline SSF assembly tasks for FTS. The FTS has become a pathfinder for many SSF issues and decisions. Its implementation as an operational system for SSF continues to provide a focus to drive out details and design issues in the areas of SSF assembly and maintenance.

The FTS received national attention when it was featured on the cover of the *Aerospace America Magazine,* February 1990 issue, which also contained a series of articles covering many aspects of the project. The FTS has been baselined for providing the remote manipulation capability for NASA's Satellite Servicer System Flight Demonstration program. The FTS is also being evaluated for providing remote manipulation system architecture and specialized science support for the President's requested Space Exploration Initiative. The ability to utilize elements of the FTS for other applications continues to be a valuable feature of the FTS system architecture that is modular in hardware, software, and operational function.

Status Of FTS Prime Contract

Since the last ATAC report was issued, Martin Marietta has made significant progress in the development of the FTS and the Development Test Flight 1 (DTF-1) mission. The configuration of the DTF-1 mission was rescoped in order to make the 1991 launch, but none of the major objectives was compromised. A new configuration was firmed up with the project, and a delta PDR was held for the new configuration on January 16 and 17, 1990. Detailed design work began immediately with emphasis given to the manipulator and its many subassemblies.

The critical path was the manipulator cabling which is a multilayer flex-cable that carries power, data, and video through all seven joints from the shoulder down to the tool plate. The number of signal paths and the EMI shielding caused the cable to grow in size, and there was a problem snaking it through the actuator joints. After a detailed analysis of the problem, it was decided that by going to 120 volts for the power source the number of leads could be significantly reduced and the cable could be worked through the actuators with enough spare traces for growth.

An engineering development model wrist was built and delivered by Schaeffer Magnetics. It is presently being used by the control system engineers to characterize the actuators for their control system design and analysis. Advanced Authorities To Proceed (AATP's) have been issued to the following subcontractors:

- Schaeffer Magnetics for the actuators
- Ford Aerospace for the end of arm tooling
- IBM for the telerobot computers
- JR3 for the force torque transducers
- Teledyne-Brown Engineering for the Multi-Purpose Experiment Support Structure (MPESS)
- Fairchild Camera for the head cameras and wrist cameras
- SMTEK for controller board fabrication

In addition to these, Martin Marietta is close to an agreement with Western Space and Marine for the development of the hydraulic manipulators for the trainers and 1-g simulators.

A mock-up of the DTF-1 task panel has been built, and analyses of camera position, field-of-view, focus, resolution, and lighting are being conducted. A mock-up of the orbiter aft flight deck is being used to study the location and human-machine interface questions concerning the workstation. Monthly crew interface meetings are held to collect crew inputs on the design. Both the task panel and the workstation mock-up are being used to develop the mission timelines.

Prototype software has been developed for the critical control path and is being run in the target environment (computer architecture). The structure for the architecture at the servo level has been defined, and the preliminary allocation of functions to the distributed processors has been made. The joint controller boards, which will be embedded within the manipulator, have been laid out. Surface mount technology was selected for mounting the chips to the board in order to achieve the highest possible density on the boards. SMTEK was selected as the vendor for the board fabrication and for application of the surface mount technology.

for cargo unpacking sequence and launch configuration. This process is worked until the potential for EVA time savings is optimized. This intense effort is paying off in quantifiable results. The result is shown in figure 1 for the third assembly flight. This figure compares the EVA time with and without FTS participation. This particular flight shows one of the greatest savings in EVA time (9 hr 23 min) and, as is the case for all assembly flights, has not been finalized. This detailed process has provided an excellent pathfinder for the realistic evaluation of future remote manipulation applications. The basic tools of task development are themselves being developed as the process is applied to SSF and other future missions. The Task Analysis Methodology sets the format and vocabulary which can be understood by the FTS functional control architecture (NASREM). The sequence of steps can be used to drive a simulation of the task or eventually the task itself as a command load to the FTS on orbit. This same process has been applied to develop task scenarios and simulations for FTS utilization to assemble complex instruments on SSF, to repair spacecraft from the Satellite Servicer System and to construct major instruments on the Lunar surface. As an example, figure 2 shows the FTS performing a task on the Cosmic Dust Collector experiment. A user-friendly automated planning tool is under development so that many potential users can develop FTS scenarios for their specific needs.

Test Flights

Configuration And Status Of Development Test Flight 1 (DTF-1)

The Development Test Flight (DTF-1) will evaluate the control and performance of the FTS manipulator and the operator workstation in a zero-g environment. Engineering data will be collected and analyzed to correlate ground simulation and analysis results with flight performance.

Flown as an attached payload on the Space Transportation System (STS), the DTF-1 consists of a teleoperated manipulator fixed mounted on a support structure in the Space Shuttle cargo bay. Also mounted to the support structure are tasks designed to study operator control and human factors issues; two head cameras and one wrist camera used for overall worksite and close up viewing; a caging mechanism system to secure the manipulator during launch and landing; and, several equipment shelves for electronic boxes. An astronaut will teleoperate the manipulator from a workstation using one mini-master hand controller and video display images from payload cameras. The DTF-1 has a flight manifested weight limit of 3300 pounds. The payload bay element is shown in figure 3.

The manipulator is approximately 5 ft long from the shoulder to the tool plate. Each manipulator joint actuator includes a brushless dc torque motor, harmonic drive transmission, torque and position sensors, brakes, cable wrap, housing and bearings. The manipulator joints are "backdriveable" which allows stowing by an EVA astronaut or by another mechanism. A hardwire "backup" system also is built into the manipulator. This system permits operator-direct control of each manipulator joint motor.

Control and data processing within the system architecture is highly distributed throughout the manipulator, data processors, and workstation. The DTF-1 processors, which are in the 80386-80387 family of computers, include one of the space station Standard Data Processor and several special purpose controllers. These controllers take on many functions, such as the control of manipulator joints, operator displays, power regulation, camera, and hand controllers.

The flight software is written in Ada with a software architecture that follows the NASREM functional architecture chosen for FTS. NASREM defines a set of standard hierarchical and horizontal modules and interfaces that correspond to different level of autonomy. By enforcing this architecture, the software can be developed incrementally and addition or exchange of new modules with better algorithms is facilitated.

The operator workstation is the point of control of the telerobot. The workstation provides the single operator with control of the manipulators in autonomous and teleoperated modes and alerts the operator when faults, failures, or out-of-limit conditions occur. The workstation consists of a Command and Data Panel, Shuttle CCTV system, one hand controller, a crew restraint system, and support avionics. These elements are configured in the Shuttle aft flight deck as shown in figure 4.

The Command and Data Panel is unfolded by the operator and mounted in front of and between the Space Shuttle Payload and On-orbit Station panels prior to use. This panel contains one monochromatic data display, a set of programmable function keys, a key pad, and discrete elements including caution and warning, power, and emergency shutdown. The payload video data will be displayed on the two Orbiter video displays located above and between the On-orbit and Payload Station panels.

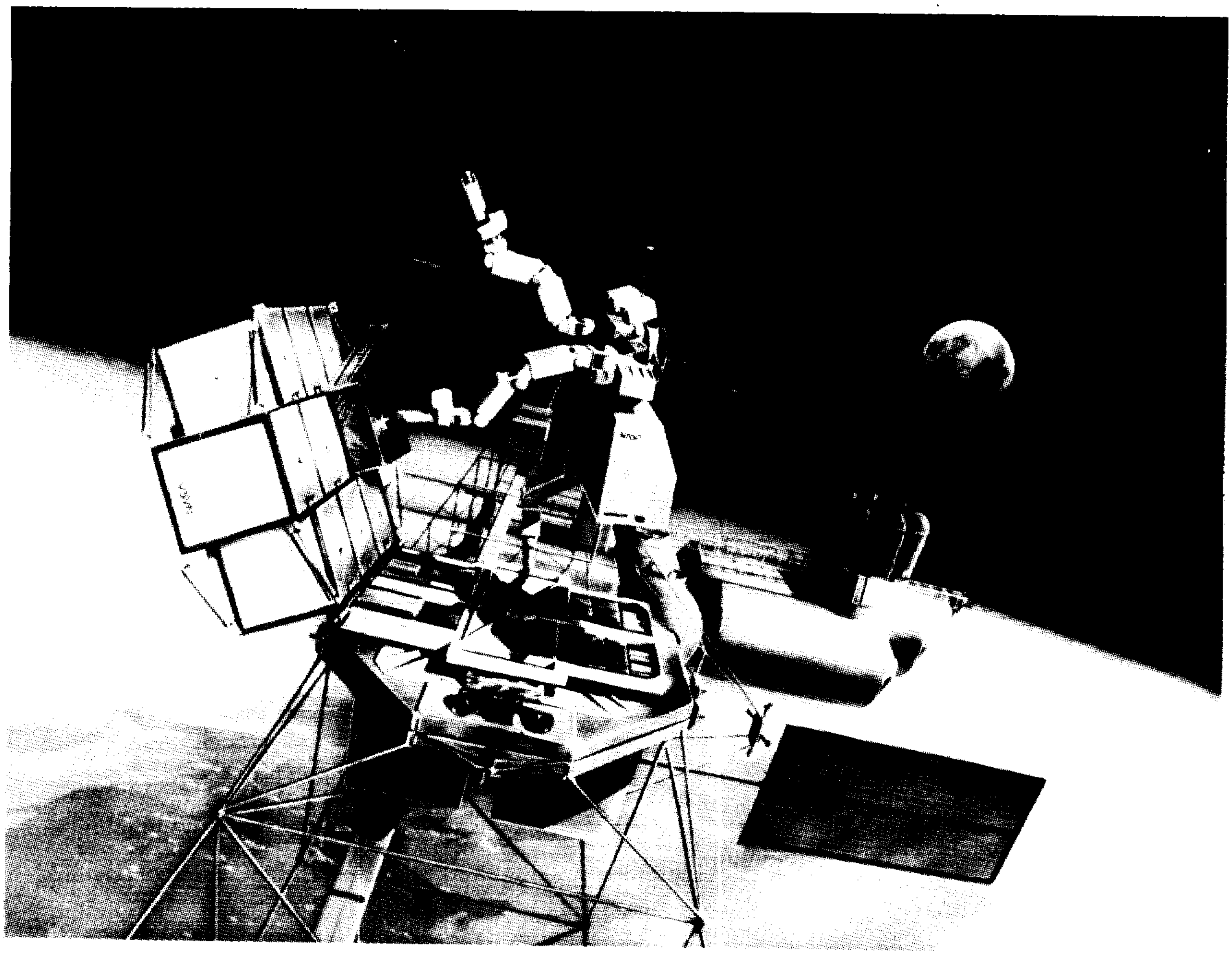

Figure 2. Flight Telerobotic Servicer.

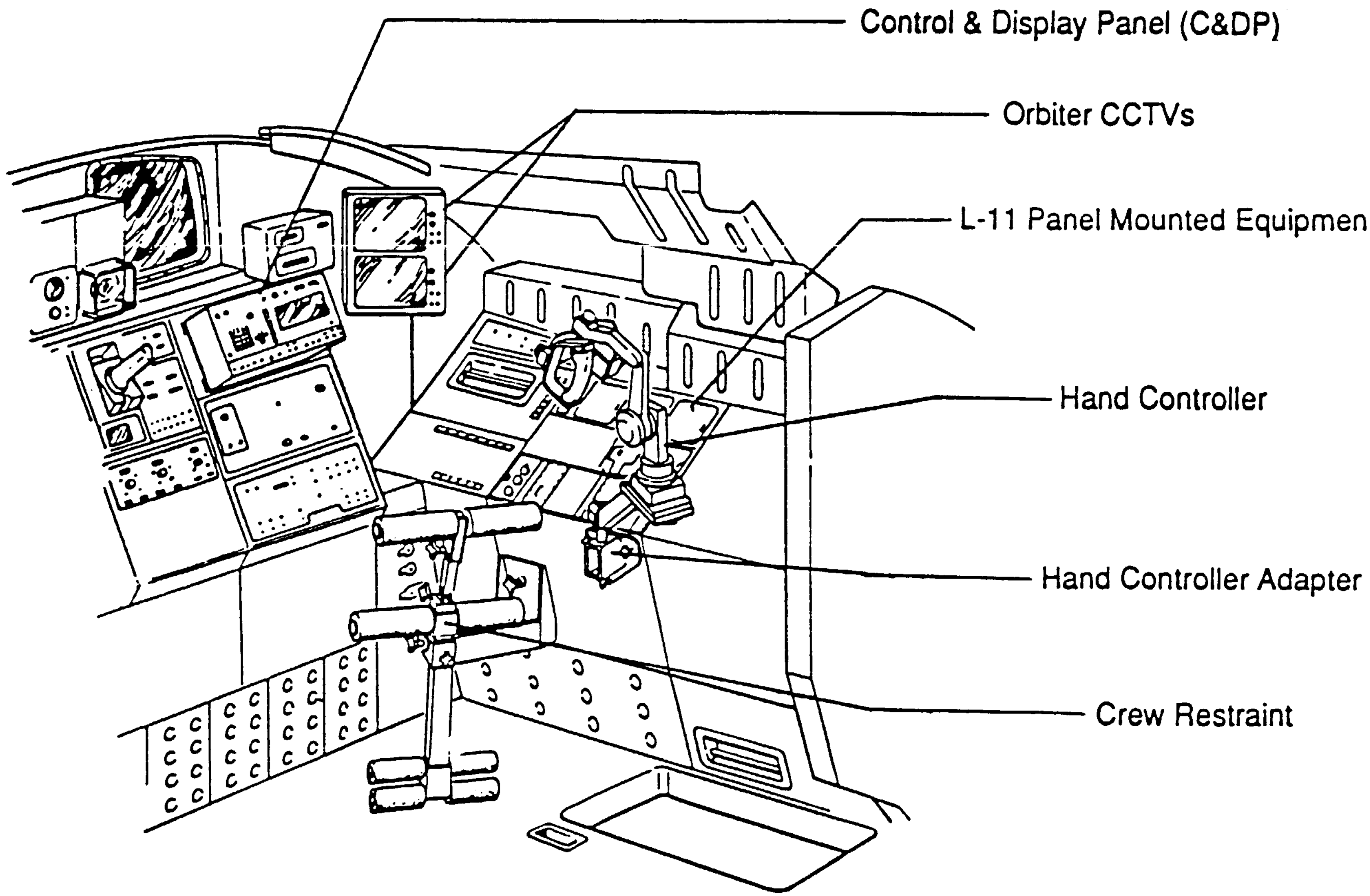

Figure 4. Space Shuttle Aft Flight Deck Element for FTS Development Test Flight (DTF-1).

APPENDIX C

References

1. NASA. 1985. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, March 1985, NASA TM 87566.
2. ASA. 1985. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 1, April-September 1985, NASA TM 87772.
3. NASA. 1986. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 2, October 1985-March 1986, NASA TM 88785.
4. NASA. 1986. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 3, April-September 1986, NASA TM 89190.
5. NASA. 1987. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 4, October 1986-May 15, 1987, NASA TM 89811.
6. NASA. 1987. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 5, May 16-September 1987, NASA TM 100777.
7. NASA. 1988. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 6, October 1987-March 1988, NASA TM 100989.
8. NASA. 1988. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 7, April 1988-September 1988, NASA TM 101691.
9. NASA. 1989. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 8, October 1988-March 1989, NASA TM 101561.
10. NASA. 1990. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 9, March 1989-July 1990.

APPENDIX E

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15. Supplementary Notes

16. Abstract

In April 1985, as required by Public Law 98-371, the NASA Advanced Technology Advisory Committee (ATAC) reported to Congress the results of its studies on advanced automation and robotics technology for use on Space Station Freedom. This material was documented in the initial report (NASA Technical Memorandum 87566). A further requirement of the law was that ATAC follow NASA's progress in this area and report to Congress semiannually. This report is the tenth in a series of progress updates and covers the period between July 13, 1989 and February 14, 1990. The report describes the progress made by Levels I, II, and III of the Office of Space Station in developing and applying advanced automation and robotics technology. Emphasis has been placed upon the Space Station Freedom Program responses to specific recommendations made in ATAC Progress Report 9, the Flight Telerobotic Servicer, the Advanced Development Program, and the Data Management System. Assessments are presented for these and other areas as they apply to the advancement of automation and robotics technology for the Space Station Freedom.

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